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PERFORMANCE OF AN ELECTROSTATICALLY AUGMENTED FABRIC FILTER PILOT PLANT

by

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Filters	Economics	Stationary Sources	14G	05C
Fabrics		Fabric Filters	11E	
Electrostatics		ESFF	20C	
Particles		Particulate		
Dust			11G	

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ABSTRACT

Laboratory experiments by Miller et al. have shown that the application of an electric field parallel to the surface of a fabric reduces the pressure drop of a dust cake deposited on the surface. In 1979 the Research Triangle Institute was awarded a contract by the U.S. Environmental Protection Agency to determine the suitability of this electrostatic augmentation technique in contemporary industrial and utility baghouses. A pilot plant consisting of side-by-side conventional and electrostatically augmented baghouses was constructed and operated initially in a pulse-jet-cleaned mode and then in a reverse-air-cleaned mode. The conventional baghouse served as a control during the experimental runs. The electrostatically augmented (ESFF) pulse-jet baghouse was able to operate stably at gas-to-cloth ratios up to 2.4 m/min, while the conventional baghouse was unable to operate above 1.5 m/min. When the ESFF and control baghouses were operated at the same gas-to-cloth ratio, the ESFF baghouse had an average pressure drop that ranged from 25% to 50% of the control baghouse. Similar results were obtained for the reverse-air-cleaned baghouses.

A preliminary analysis of the economic feasibility of pulse-jet-cleaned ESFF baghouses has been completed. An ESFF pulse-jet baghouse designed for a gas-to-cloth ratio of 2.4 m/min would have a total annual cost that is 30% lower than a conventional pulse-jet baghouse designed for a gas-to-cloth ratio of 1.2 m/min. Evaluation of the economics of the reverse-air-cleaned ESFF baghouse is still underway as are further pilot-plant and laboratory studies designed to elucidate the mechanism of ESFF.

Introduction

The use of fabric filters to remove particles from gas streams is well established in industrial practice and of growing importance for electrical utility boilers. For utility boilers, the fabric filter has an advantage over other particulate control equipment with respect to removal efficiency, and it is roughly competitive in price. However, fabric filtration operating experience on utility boilers is limited, and enough questions have been raised by unexpectedly high baghouse pressure drops to cause caution in the industry.

Miller et al. (1) developed the concept of electrostatic augmentation of fabric filtration (ESFF) as a means of reducing the pressure drop associated with fabric filters. Laboratory work suggested that an electric field that is applied parallel to the filter surface modifies the dust cake in such a way as to yield a lower flow resistance. In some cases, the pressure drop was reduced by more than 50%, and, in addition, the penetration was found to be lower. In 1979, the U.S. Environmental Protection Agency awarded a contract to the Research Triangle Institute to determine the applicability of this electrostatic enhancement technique to contemporary industrial and utility boilers. Complete details of the pilot-plant construction and operation are contained in the reports by VanOsdell et al. (2,3).

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(1) B. Miller, G. Lamb, et al. Studies of Dust Cake Formation and Structure in Fabric Filtration. EPA-600/9-81-023, U.S. Environmental Protection Agency, August 1983.

(2) D.W. VanOsdell, M.B. Ranade, G.P. Greiner, and D.F. Furlong. Electrostatic Augmentation of Fabric Filtration: Pulse-Jet Pilot Unit Experience. EPA-600/7-82-062, U.S. Environmental Protection Agency, November 1982.

(3) D.W. VansOsdell and D.F. Furlong. Electrostatic Augmentation of Fabric Filtration: Reverse-Air Pilot Unit Experience. Draft report prepared for U.S. Environmental Protection Agency.

Table 1. Waynesboro, Virginia, Boiler House

Number of boilers:	4
Type:	Pulverized coal with oil cofiring capability
Capacity:	68,200, 75,000, 75,000, and 70,000 kg/hr of steam at 2,860 kPa
Operation:	Continuous
Normal load:	164,000 kg steam/hr
Load variation:	(a) 143,000 kg/hr minimum to 209,000 kg/hr maximum over a year. (b) Variation up to 18,000 kg/hr within an 8-hr shift. (c) Variation up to 27,000 kg/hr within a 24-hr period.
Coal:	Highly variable
Sulfur:	0.6 - 2.9 percent, average of about 1.3 percent.
Ash:	6 - 27 percent, average of about 13 percent.
Emission control device:	Reverse-air baghouse

Pilot Plant

The basis of the ESFF pilot-unit test program was parallel operation of a conventional baghouse and an electrostatically augmented baghouse. Boiler and coal variations in an operating boiler were expected to be too large for successful testing to be done serially in time in a single baghouse. Operating experience has borne out the desirability of this approach.

The pilot unit was operated on a slipstream from the coal-fired industrial boiler. The plant boiler characteristics are summarized in Table 1. A slipstream was extracted from the breeching of the plant's baghouse and used as the dust source for the pilot plant. The slipstream was split to provide equal flow to the side-by-side baghouses.

A schematic of the ESFF pilot unit is provided in Fig. 1. All ductwork was passed through a trailer outfitted as a laboratory to provide a suitable environment for test work. The approximate locations of flow control and isolation valves are indicated in Fig. 1. Particle mass and size distribution measurements were made through test ports in the duct walls.

The flowrate was monitored at the inlet and outlet of each baghouse. The baghouse pressure drop was measured from pressure taps located just above and below the tubesheet of each baghouse. The baghouse pressure drop was continuously recorded.

When operated in the pulse-jet mode, blow pipes with 0.63 cm holes centered above the bags were installed in the baghouse. The cleaning pulse came from a reservoir with a pressure of 670 kPa and lasted 50 ms. The

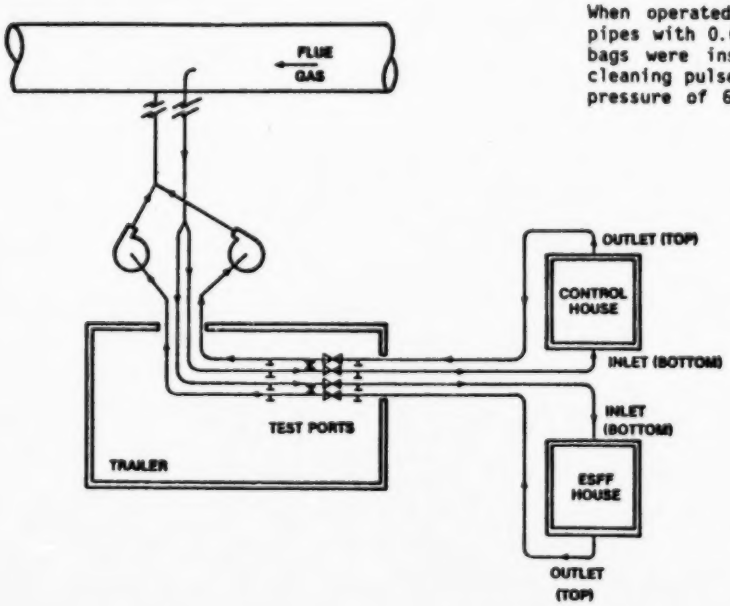

Figure 1. Schematic diagram of ESFF pulse-jet pilot unit.

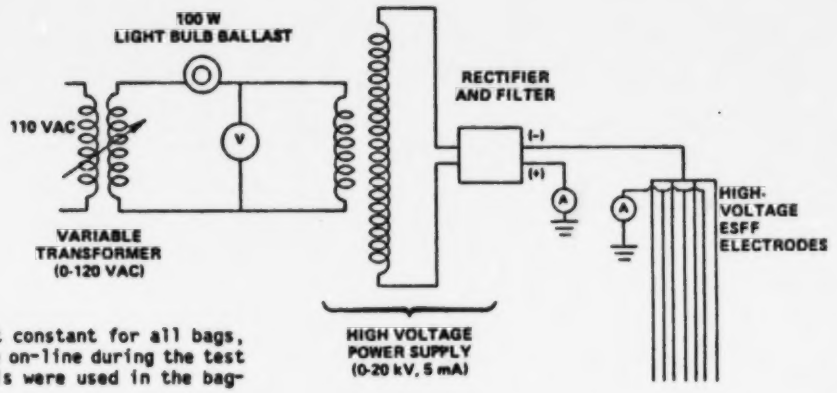

Figure 2. High voltage ESFF electrical circuit.

pulse energy was kept constant for all bags, and cleaning was done on-line during the test programs. No venturis were used in the baghouse.

When operated in the reverse-air mode, cleaning was done off-line. The compartment to be cleaned was taken off-line and cleaned with ambient air warmed up to the operating temperature of the baghouse. Each compartment was cleaned twice during a cleaning cycle because laboratory data indicated that ESFF was most advantageous with well-cleaned bags. The control baghouse was cleaned last to give it any advantage in the comparison.

The electrical hardware for the pilot unit consisted of high-voltage DC power supplies, current and voltage instrumentation, and the ESFF electrodes. The power supplies and instrumentation are shown schematically in Fig. 2. Five identical power supply systems were provided for the ESFF baghouse. This provided flexibility in powering the ESFF electrodes and backup capability. As no more than five bags were installed during the test program, it was possible to monitor bag current and power supply current separately for each bag.

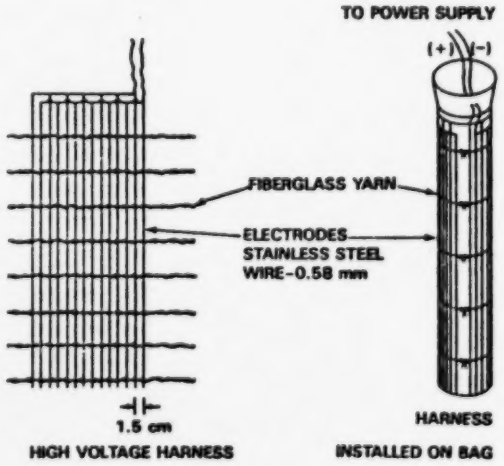

Figure 3. Harness for applying electric field parallel to the surface of a fabric filter bag.

One of the challenges of the pilot test program was to determine a suitable method for delivering the current to the bags. For the pulse-jet baghouse, three different electrode designs were used during the test program. The first design used was the harness developed by Textile Research Institute (TRI). This design is shown in Fig. 3. The harness consisted of parallel, alternately charged stainless steel wire electrodes glued to fiberglass connecting yarns. The entire assembly was tied to the outside of the bag, and the electrical connections were made by connecting the electrodes and high voltage leads to opposite ends of bolts which were passed through the bag cuff. This outside electrode harness was used during most of the test program. Several problems were inherent in this design. The harness had the potential of restricting bag movement and reducing cleaning efficiency. It was relatively fragile and difficult to install, and the cage within the bag required coating to electrically insulate it from the harness on the outside of the bag. The harness adhesive and the baghouse cage coating were both adversely affected by the high temperature flue gas environment. In spite of these difficulties, the harnesses were used successfully during a significant portion of the test program.

The cage-electrode design shown in Fig. 4 was developed to overcome the difficulties associated with the harness. In this design, the bag support cage was modified so that alternate wires of the cage could be electrically isolated. Alternate wires were charged and grounded to generate the electric field. This design was avoided at

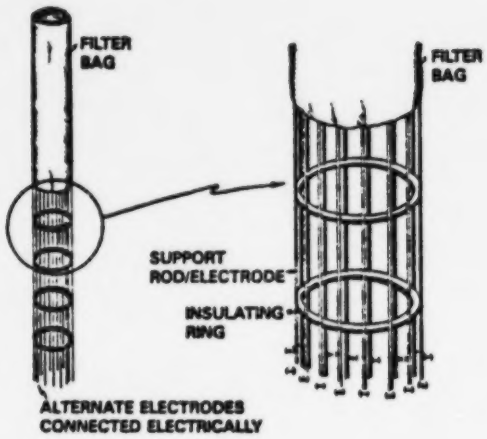

Figure 4. Inside electrodes utilizing insulating ring spacers.

first because Miller's data (1) suggested that the ESFF effect was considerably reduced with the electrodes on the clean side of the fabric. The pilot unit results were more favorable than the laboratory results; the inside cage worked as well as the harness but without the inherent problems.

The presence of the bag support cage in the pulse-jet baghouse provided a natural means for supplying current to the bags. In a reverse-air baghouse, there are no such cages so the development of suitable electrode designs was more troublesome. The harness electrode used on the pulse-jet baghouse was found to be inadequate for the reverse-air test series. Instead, a rigid cage similar to the one shown in Fig. 4 was used on the outside of the bag to provide the electric field. All of the pilot plant studies were conducted with this rigid electrode and with a slightly modified version that was more flexible.

While the rigid cage was adequate for the purposes of the pilot test program, it was recognized that for ESFF to be a viable technology for reverse-air baghouses, then it would be necessary to develop fabrics with woven-in electrodes. A number of techniques were investigated for providing electrodes integral to the fabric. Although difficult to work with from a weaver's standpoint, woven-in stainless steel yarn became the electrode of choice because of its durability. Bags were constructed from this fabric and tested in the pilot unit. The performance of the woven electrode bag was essentially the same as that of the cage-electrodes.

Test Program

The pilot plant test program was run in two phases: the pulse-jet phase and the reverse-air phase. The first goal of the test program was to demonstrate that the ESFF effect existed. Once the benefits of ESFF had been observed and difficulties with the hardware had been corrected, studies were begun to assess the effect of various operating characteristics, including applied field strength, face velocity, electrode design, and fabric type. The details of the test program and the results for the pulse-jet baghouse will be reviewed first, followed by the reverse-air results.

During start-up of the baghouse, the objective was to identify any problems associated with the design and construction of the baghouse. Both of the baghouses were run as conventional pulse-jet units using Teflon® felt bags. Problems with in-leakage of ambient air and heat loss were identified and corrected. Proof of satisfactory inlet conditions was then obtained by comparing the tubesheet pressure drops for the two baghouses. The pressure drops were found to remain well within 10% of each other. Tests of the inlet mass loadings agreed when run simultaneously, although considerable variation with time was evident.

Once the start-up was completed, a test program was begun to demonstrate the presence of the ESFF effect. Both of the baghouses were fitted with napped Teflon® felt bags, and one set of the bags was wired for ESFF with the harness electrode described earlier. The compartments were brought up to operating temperature, the ESFF bags were set to 4 kV/cm, and the dirty gas flow was introduced to the baghouses. The face velocity was maintained at 1 cm/s, and cleaning was initiated when the pressure drop reached 0.25 kPa. This period was planned to "condition" the new bags.

After the conditioning period, the cleaning cycle was changed from pressure controlled to time controlled. The baghouses were operated for several days at identical face velocities (3 cm/s) and the field voltage was maintained at 5.9 kV/cm. Fig. 5 shows a comparison of the pressure traces for the ESFF and the control baghouses for a 15-minute cleaning cycle. The ESFF baghouse maintained a lower pressure drop after cleaning (residual pressure drop), and the rate of pressure increase with time was lower than for the control baghouse. These results represent stable operating points.

By the end of this first test run, it was recognized that the harness electrodes were inadequate for prolonged operation of the baghouse. The support-cage electrodes were designed and installed in the ESFF baghouse,

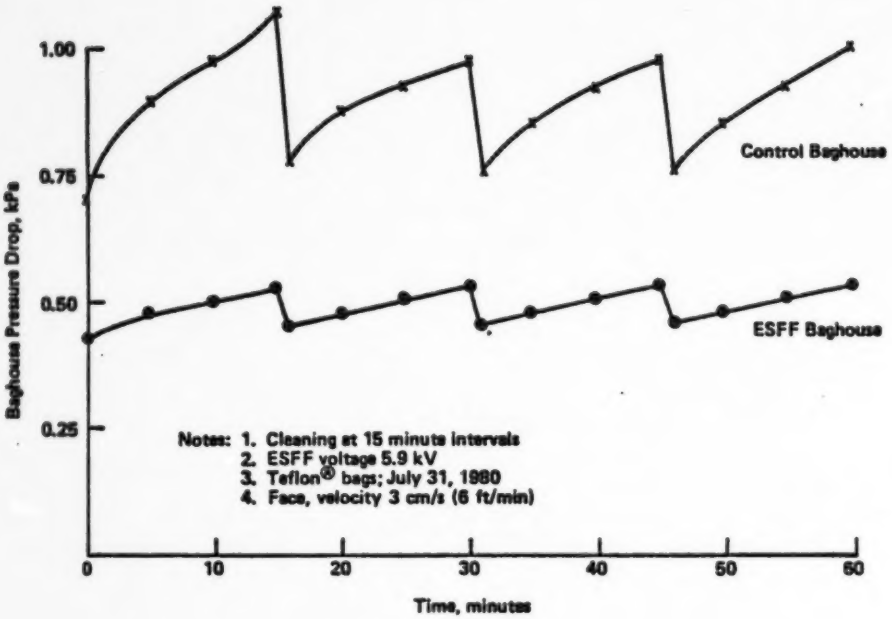

Figure 5. Pressure drop plot for pilot baghouse.

and the above experiment was repeated to determine how well the inside electrodes would function. The results with the outside electrodes were essentially the same as shown in Fig. 5.

The next step was to examine the effect of field strength on the ESFF enhancement. A series of test runs were performed during which the field strength was varied from 0 to 5 kV/cm. The baghouse was allowed to achieve stable operation at each voltage level. A quantity called the pressure-drop ratio (PDR) was defined as the ratio of the pressure drop rise across the ESFF baghouse to the pressure drop rise across the control baghouse during simultaneous cycles. Fig. 6 shows the dependence of PDR on electric field strength. The points labeled 'T' were measured at the ESFF pilot unit operating with the Teflon® bags. The points labeled 'G' are the results obtained with woven glass bags. The curve labeled 'TRI Lab Data' is from Miller (1). The differences between the TRI Lab Data and the field data are likely due to the differences in the test conditions--temperature, dust loadings, experimental protocols, etc.

The data shown in Fig. 6 actually represent two different types of Teflon® felt bags and one type of woven glass bag. The Teflon® bags were made of 23 oz napped felt and a new single-sided felt. The glass fabric was a J.P. Stevens 648-45 woven with a bulked fill yarn and coated with a 10% Teflon® B finish. The differences in the results are attributed to differences in the surface characteristics of the different fabrics. Apparently the fluffier surface of the Teflon® bags was more effective at maintaining a porous, low drag dust cake when the field was applied.

The pressure-drop ratio describes the relative pressure drops of the two baghouses, but there is another, equally important aspect of ESFF: the reduction of residual pressure drop. It seems that the presence of the electric field at the surface of the fabric prevents dust particles from penetrating deeply into the fabric; the fluffier the fabric surface, the more pronounced is the ESFF effect. Fig. 7 is an example of the difference in the residual pressure drops. At the beginning of the test the ESFF and the control baghouse were cleaned several times to achieve similar residual pressure drops. The baghouses were then operated at a face velocity of 2.5 cm/s. The residual pressure drop of the control baghouse increased rapidly, while the ESFF baghouse only changed slightly. Typically, the residual pressure drop of the ESFF baghouse was 58% of that of the control baghouse.

The ability of the ESFF baghouse to operate at a lower residual pressure drop suggested that it might be possible to operate at an

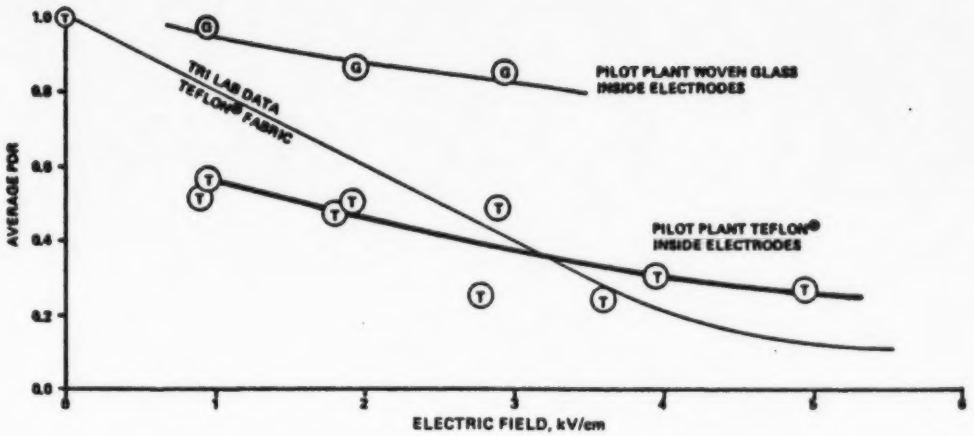

Figure 6. PDR-field strength relationship for Teflon® and glass fabrics.

increased face velocity without blinding. A test of increased face velocity operation was conducted over a period of several days. The control baghouse was operated at 2 cm/s, and the ESFF baghouse was operated at 2, 3, 4, and 5 cm/s face velocities. The experiment was started with clean bags in the ESFF baghouse maintained at 3.6 kV/cm. The bags were conditioned at 2 and 4 cm/s. When the bags had been conditioned, the face velocity was changed to 3 cm/s with a 30-minute cleaning cycle, and stable operation was achieved. Next, the face velocity was raised to 4 cm/s. The ESFF baghouse operated well while on a cleaning cycle of 15 minutes or less but could not operate with longer cleaning cycle times. In all, the baghouse operated at 4 cm/s for 7 days, and stable operation was maintained over a 2-day period at 5 cm/s with a 10-minute cleaning cycle.

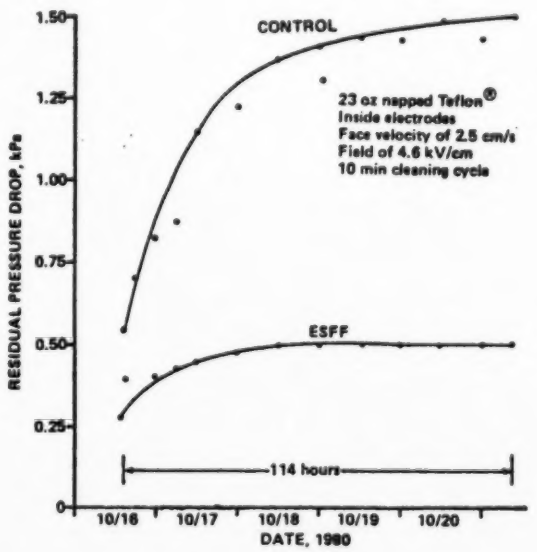

Figure 7. Residual pressure drop for ESFF and control baghouses.

Throughout the pulse-jet test program, the ESFF and control baghouses maintained essentially the same penetration (about 2%). This is contrary to the results of Miller, who reported that penetration was lower with ESFF. The difference is attributed to the differences in the test conditions between the lab and field.

The second phase of the pilot test program was devoted to evaluation of the applicability of ESFF technology to reverse-air baghouses. The pilot unit was reconfigured to operate as a standard reverse-air baghouse with one baghouse operating as an ESFF unit. This test program was oriented more towards development of suitable electrode types, and the test program was not as extensive as the pulse-jet program. The first set of runs was conducted with a rigid cage similar to the pulse jet cage mounted on the outside of the bag. At the outset of the program, it was uncertain whether or not the ESFF effect would be significant due to the fact that the electrodes were mounted on the clean side of the fabric. The results of the test indicated that the ESFF effect was present and significant, with an average ESFF pressure drop 30% below that of the control baghouse at a face velocity of 2 cm/s. Similar results were obtained when the bags with woven-in electrodes were tested.

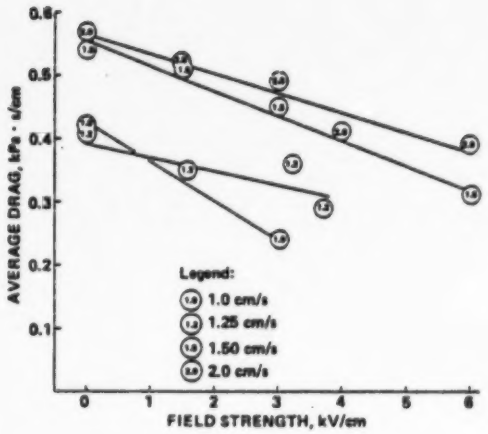

Figure 8. Drag as a function of field strength and face velocity.

The effects of electric field strength and face velocity on drag were investigated during three test periods. Data from these tests are presented in Fig. 8. Most of the data points are averages of 2 to 4 days of operation. There is a clear dependence of average drag on field strength at all face velocities tested, as well as a significant dependence of average drag on face velocity. Halving the face velocity at any field strength reduced the average drag by 25 to 50%. Testing also revealed that the bag current should never be turned off except during cleaning. Operation of an ESFF bag without the ESFF field allows dust to penetrate deeply into the bag fabric, drastically reducing the ESFF effect in subsequent tests of the bag.

As with the pulse-jet test program, the mass removal efficiencies of the two baghouses were about the same. The overall mass penetrations amounted to about 0.2%.

Economics

The demonstrated improvements in pressure-drop performance of an ESFF baghouse must be reflected in the economics of the unit to be of practical use. The economic potential of the ESFF concept was explored by comparing the total annual costs of conventional pulse-jet and reverse-air baghouses with those of similar baghouses equipped with ESFF hardware. The results presented below are based on coal-fired boilers; the effects of other operating conditions (different dust, temperature, etc.) on cost are uncertain because there is no ESFF operating experience on which to base the calculations.

There are two methods of realizing the economic benefits of ESFF in a new baghouse:

1. Design the ESFF baghouse to be the same size as a conventional baghouse, and use the ESFF effect to produce lower pressure drops and lower operating costs.

2. Design the ESFF baghouse to operate at the same average pressure drop as a conventional baghouse but with a correspondingly smaller size. In this case the savings would be realized in lower capital costs.

For the purposes of this study, only the second option was evaluated. The first option is appropriate for the retrofitting of a conventional baghouse with ESFF hardware for the purpose of lowering the pressure drop. At the current interest rates, it was felt that the second option would prove to be much more attractive.

For the evaluation of the pulse-jet baghouse; a simple model of capital and operating costs for pulse-jet baghouses was developed. The cost of a pulse-jet baghouse module was estimated and compared with vendor quotes. Based on the estimated cost and the vendor quotes, a baghouse module cost of $\$161/m^2$ was assumed. Multiplication factors for direct and indirect costs were applied to account for the cost of installing the baghouse. The capital recovery cost was calculated assuming a baghouse lifetime of 15 years and an interest rate of 14%.

Based on the pilot-plant experience, a prototype design for ESFF hardware was developed, and estimates of equipment costs were obtained. The cost of a pulse-jet baghouse with ESFF hardware was estimated to be $\$183/m^2$. The installed cost of the ESFF baghouse was calculated using the same direct and indirect cost factors as for the conventional baghouse.

Annual operating cost was assumed to include four components:

1. fan electrical power cost,
2. cleaning system electrical power cost,
3. equipment maintenance, and
4. bag replacement.

No increased electrical cost was assigned to the ESFF baghouse, as pilot-plant experience has shown it to be negligible. Equations were developed to estimate these costs based on the face velocity and pressure drop in the baghouse. A simple model based on the field data indicated that the pressure drop of the conventional baghouse could be predicted by the equation:

$$\Delta P_{conventional} = 0.75 + 0.75 \times v$$

where ΔP has units of kPa, and v is the face velocity in cm/s. Similarly for the ESFF baghouse:

$$\Delta P_{ESFF} = 0.75 + 0.25 \times v \quad .$$

The factor of 0.75 was assumed to account for the pressure drop of the ductwork.

Based on this model, the Total Annual Cost of a conventional baghouse operating on a coal-fired boiler producing 1130 m^3/hr of flue gas was estimated. The same calculations were performed assuming three different sizes of ESFF baghouses. Fig. 9 presents a comparison of the results as a function of electricity cost. While the ESFF baghouse is only marginally competitive at a face velocity of 2 cm/s, the benefit of ESFF is clearly evident at higher face velocities. Note that a conventional baghouse operating at a face velocity of 2 cm/s would be at the limits of the technology; whereas, the pilot-plant experience has demonstrated the ability of an ESFF baghouse to operate successfully at 3 cm/s, if not at 4 cm/s. Based on these calculations, it appears that an ESFF baghouse operating at 4 cm/s would have a total annual cost 30% less than that of a conventional baghouse operating at 2 cm/s.

A similar analysis was performed for the reverse-air ESFF technology. The model of Viner and Ensor (4) was used to estimate the costs of a conventional reverse-air baghouse. Based on the experience gained at the pilot plant, a prototype design for ESFF hardware was developed and incorporated into the cost model. Since the cost of the power supplies and other electrical equipment is relatively small, the cost of special ESFF bags with woven-in electrodes becomes a significant portion of the ESFF capital cost. Considering the fact that the bags must be replaced regularly, the viability of ESFF technology rests on the tradeoff between pressure drop and cost of these ESFF bags.

At the pilot plant, the conventional reverse-air baghouse was able to maintain an average pressure drop of 0.42 kPa at a face velocity of 1 cm/s; whereas, the ESFF baghouse had an average pressure drop of 0.19 kPa at the same face velocity. At a face velocity of 2 cm/s, the ESFF baghouse had an average pressure drop of 0.65 kPa. No conventional reverse-air baghouses are known to operate reliably at this higher face velocity. Assuming full-scale conventional and ESFF baghouses would operate with the characteristics of the pilot plant, the total annual operating cost was estimated for an ESFF baghouse operating on a 500-MW coal-

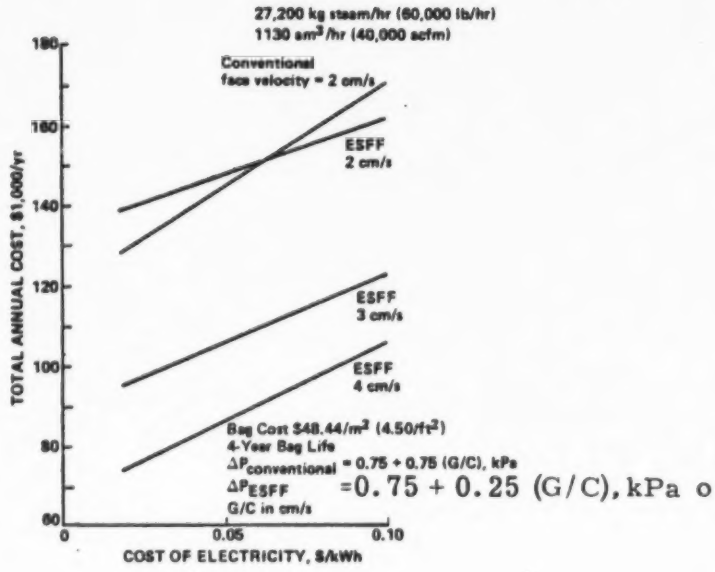

Figure 9. Pulse-jet baghouse cost: pulverized coal industrial boiler.

fired electric utility plant. ESFF bag costs of 2, 3, and 4 times the cost of conventional bags were used in the comparison. The conventional baghouse was found to have a total annual cost of $3,840,000; whereas, an ESFF baghouse operating at 2 cm/s and a bag cost 3 times the cost of conventional bags would have a total annual cost of $3,430,000. This represents an annual savings of 11% for the ESFF baghouse. If the ESFF bag cost only twice the cost of conventional bags, then its total annual cost would be only $3,160,000. This represents an annual savings of 18%.

Summary

A pilot plant was designed and constructed for the purpose of demonstrating the benefits of electrostatic stimulation of fabric filtration for both pulse-jet- and reverse-air-cleaned baghouses. The use of identical, side-by-side baghouses permitted direct evaluation of test results. The pilot test program clearly demonstrated the presence and magnitude of electrostatic enhancement for the case of coal fly ash collected on Teflon® fabrics. A preliminary economic evaluation indicates that ESFF is an economically feasible technology for both types of baghouses. A large-scale pilot program is now underway to demonstrate ESFF on full-size (10 m) reverse-air bags, and laboratory research is underway to elucidate the mechanism of pressure drop reduction in electrostatically stimulated fabrics.

(4) A.S. Viner and D.S. Ensor. Computer Programs for Estimating the Cost of Particulate Control Equipment. IERL-RTP-1496, U.S. Environmental Protection Agency.